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A SEARCH FOR RADIO EMISSION FROM TYPE IA SUPERNOVAE

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ABSTRACT

We present and discuss the radio observations of 27 Type Ia supernovae (SNe Ia) observed over two decades with the Very Large Array. No SN Ia has been detected so far in the radio, implying a very low density for any possible circumstellar material established by the progenitor, or progenitor system, before explosion. We derive 2σ upper limits to a steady mass-loss rate for individual SN systems as low as $\sim 3 \times 10^{-8}$ $M_\odot$ yr^{-1}, discriminating strongly against white dwarf accretion via a stellar wind from a massive binary companion in the symbiotic star, an example of the "single degenerate" scenario. However, a white dwarf accreting from a relatively low mass companion via a sufficiently high efficiency ($> 60 - 80$ %), Roche lobe overflow is still consistent with our limits. The "double degenerate" merger scenario also cannot be excluded.

Subject headings: (stars:) supernovae: general, radio supernovae, stars: mass loss, (stars:) white dwarfs, (stars:) binaries: symbiotic, (stars:) binaries: close, radio continuum: stars

1. INTRODUCTION

Supernovae (SNe) are among the most energetic events in the Universe. Determining the properties of the progenitor stars or stellar systems remains an important unsolved problem in astrophysics. Few SNe have had their progenitor stars directly identified but the post-explosion radio emission from SNe provides insight into the nature of the progenitor stars and their last stages of evolution. The phenomenon of radio SNe (RSNe) has been best modeled by synchrotron emission resulting from the interaction of the SN shock with circumstellar material (CSM) established by pre-SN mass-loss from the progenitor system before the explosion; likely from the progenitor itself, or possibly from the progenitor's companion in the case of a binary system (Chevalier 1982a, 1982b; Sramek et al. 1984, Weiler et al. 1986).

Although it has been generally accepted that Type Ia SNe (SNe Ia) result from the thermonuclear explosion of a white dwarf (WD) star (e.g., Nomoto, Thielemann & Yokoi 1984, Branch et al. 1985), two fundamental questions remain: 1) Is the exploding WD of Chandrasekhar or sub-Chandrasekhar mass? 2) If the former, how does the exploding WD (typically ~ 0.6 $M_\odot$; e.g., Ritter & Burkert 1986) accumulate enough mass to approach the Chandrasekhar limit of ~ 1.4 $M_\odot$, prior to explosion? In the so-called "single-degenerate" scenario (Nomoto et al. 1984), the source of the accreted material is provided by interaction with a non-degenerate companion, such as a low-mass main sequence star, a subgiant, or a giant star (see the reviews by Branch et al. 1995, Livio 2001). Under the "double-degenerate" scenario (Iben & Tututkov 1984, Webbink 1984) the explosion is triggered by the merger of two degenerate stars, such as WDs or neutron stars.

The nature of SN Ia progenitors has become even more important in the last decade because of their fundamental importance for cosmology (e.g., Riess et al. 1998, Perlmutter et al. 1999, Perlmutter et al. 2003). Unfortunately, we are in the embarrassing situation that, even as confidence in the astounding new cosmological results increases, we still have little knowledge of the physical origin of the luminous SNe Ia explosions on which this result is at least partly based.

Observations of SNe Ia in the radio can provide a powerful constraint on the Chandrasekhar mass explosion mechanism in that the mass exchange required for the single-degenerate scenario should establish an enhanced CSM density, however tenuous, near the SN progenitor, while the double-degenerate scenario should not, unless the two coalescing WDs are in a common envelope (see Livio 2003). Thus, radio detection of the blastwave interaction with such a CSM would not only support the single-degenerate scenario, but also provide information on its extent, density, and structure.

To test the single-degenerate case for a symbiotic star progenitor system (in which a red giant donates mass to the WD via a wind), Boffi et al. (1995) modeled any putative, fast-evolving radio light curves for the SN Ia 1986G through analogy with the radio light curves for the SN Ib 1983N (Sramek et al. 1984, Weiler et al. 1986). From radio observations of SN 1986G conducted one week before optical maximum (i.e., early enough to adequately test the Boffi & Branch prediction), Eck et al. (1995) concluded, based on a lack of detected radio emission, that this SN probably did not arise from a symbiotic star system. Eck et al. stressed that further searches for prompt radio emission from other SNe Ia were clearly necessary to test this and other models.

Numerous radio observations have been obtained for

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27 SN Ia using the Very Large Array (VLA)[8] as part of a SN monitoring program we have been conducting for more than two decades. In our program we have considered only SN Ia exploded in external galaxies and we have not included any of the historical SN Ia that have occurred in the Milky Way. Earlier results of SN Ia observations were presented by Weiler et al. (1986, 1989) and Weiler & Sramek (1988). Unlike Type II and Type Ib/c SNe, no SN Ia has yet been detected as a radio emitter, even when observed quite promptly after explosion (e.g., SNe 1981B and 1980N; Weiler et al. 1986, 1989) or quite nearby (e.g., SN 1972E; Cowan & Branch 1982, 1985, Weiler et al. 1989). Here, we present our new results with improved sensitivity and time and frequency sampling and discuss the possible implications for the nature of the SN Ia progenitors.

2. RADIO OBSERVATIONS

The sample of observed SNe Ia consists of those generally with $m \leq 14$ mag occurring between 1982 and 2002. The sample includes the "Branch Normal" SNe Ia 1992A (e.g., Kirshner et al. 1993) and 1994D (e.g., Richmond et al. 1995), as well as the overly luminous SN 1991T (e.g., Filippenko et al. 1992a; Schmidt et al. 1994), the subluminous SN 1991bg (e.g., Filippenko et al. 1992b; Leibundgut et al. 1993), and the peculiar SN 1986G (e.g., Phillips et al. 1987). Two SNe, 2002bo (Szabo et al. 2003) and 2002cv (Di Paola et al. 2002), both occurred within a few months in the same host galaxy, NGC 3190.

The SNe were observed with the VLA in a number of array configurations at, primarily, 6 cm wavelength (4.8 GHz), although observations for several objects were also made at 20 cm (1.4 GHz), 3.6 cm (8.4 GHz), 2 cm (15 GHz), 1.3 cm (22 GHz), and 0.7 cm (43 GHz). The techniques of observation, editing, calibration, and error estimation are described in previous publications on the radio emission from SNe (e.g., Weiler et al. 1986, 1990, 1991). For the SN 1986G in NGC 5128 observations, the presence of the very radio bright galaxy nucleus Centarus A required the additional analysis steps of first self-calibrating on, and then removing from the *uv*-data, the components of the bright radio galactic nucleus, before producing the final maps of the SN field.

The SNe Ia which were observed are listed in table 1. These include observations already described in Weiler et al. (1986) and Weiler et al. (1989). Column 1 lists the SN name, columns 2 and 3 list the date and magnitude at optical maximum (if available; if not, the date and magnitude at discovery are listed), and columns 4 and 5 give the right ascension (R. A.) and declination (Decl.) in epoch J2000 coordinates which were used for the radio observations. Columns 6 and 7 list the parent galaxy name and Hubble type. The radio results are listed in Table 1. Column 1 of that table lists the SN name, and column 2 the date of observation. Column 3 lists the estimated age of the SN in days after explosion, and column 4 the VLA configuration of the observation. Columns 5–10 list the measured rms (1σ) error, in mJy, in the resulting maps at 20, 6, 3.6, 2, 1.3, and 0.7 cm wavelengths, respectively.

[8] The VLA telescope of the National Radio Astronomy Observatory is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation.

In Figure 1 we present the 2σ spectral luminosity upper limits for SNe Ia at the wavelengths of 20, 6, 3.6, and 2 cm. The data were rather sparse at 1.3 cm (1 point) and 0.7 cm (1 point), so those two frequencies are not shown. In Figure 2 we show the limits for two of the SNe Ia (SN 1989B and SN 1998bu) which were particularly well observed. None of the SNe Ia was detected as a source of radio emission, consistent with the previous results from Weiler et al. (1986, 1989).

3. RADIO LIGHT CURVE MODELING

Following Weiler et al (2002) and Sramek & Weiler (2003) we adopt a parameterized model that, in view of the non-detection results, has been simplified to include only the intrinsic synchrotron emission from relativistic electrons created at the SN shock front and possible free-free (f-f) absorption by thermal electrons in a surrounding homogeneous CSM that has been ionized by the SN explosion itself. In this case, we can write

$$S(\mathrm{mJy}) = K_1 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha} \left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\beta} e^{\tau_{\mathrm{CSM_{external}}}} \qquad (1)$$

with

$$\tau_{\mathrm{CSM_{external}}} = K_2 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1} \left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\delta} \qquad (2)$$

with K_1 and K_2 corresponding, formally but not necessarily physically, to the flux density (K_1) and homogeneous (K_2) absorption at 5 GHz one day after the explosion date, t_0. The term $\tau_{\mathrm{CSM_{external}}}$ is produced by an ionized medium that homogeneously covers the emitting source ("homogeneous external absorption") and is near enough to the SN progenitor that it is altered by the rapidly expanding SN blastwave. The radial density (ρ) distribution of this homogeneous, external absorbing medium, if established by a constant mass-loss rate ($\dot{M}$), constant velocity (w_{wind}) pre-SN stellar wind, is r^{-2} (*i.e.,* $\rho \propto \frac{\dot{M}}{w_{\mathrm{wind}}\ r^2}$). The value of δ in Equation 2 describes the actual radial density, if different from r^{-2}, for a constant shock velocity. The absorbing medium is assumed to be purely thermal, singly ionized gas, which absorbs via free-free (f-f) transitions ! with frequency dependence $\nu^{-2.1}$ in the radio.

Since the f-f optical depth outside the blastwave emitting region is proportional to the integral of the square of the CSM density over the radius and, in the simple model (Chevalier 1982a,b) the CSM density decreases as r^{-2}, the external optical depth will be proportional to r^{-3}. With the blastwave radius increasing as a power of time, $r \propto t^m$ (with $m \leq 1$; i.e., $m = 1$ for undecelerated blastwave expansion), it follows that the deceleration parameter, m, is

$$m = -\delta/3. \qquad (3)$$

The success of the basic parameterization and modeling has been shown in the good correspondence between the model fits and the data for all RSN types: e.g., Type Ib SN1983N (Sramek et al. 1984), Type Ic SN1990B (VanDyk et al 1993a), Type II SN1979C (Weiler et al 1991, 1992a, Montes et al. 2000) and SN1980K (Weiler

et al. 1992b, Montes et al. 1998), and Type IIn SN1988Z (VanDyk et al. 1993b, Williams et al. 2002).

For the case of a steady pre-SN stellar wind Weiler et al (1986, 2002), and Weiler, Panagia & Montes (2001) have shown that the mass-loss rate can be derived directly from the measured (f-f) optical depth as:

$$\frac{\dot{M}(\mathrm{M_\odot\ yr^{-1}})}{(w_{\rm wind}/10\ \mathrm{km\ s^{-1}})} = 3.0\times10^{-6}\ <\tau_{\rm eff}^{0.5}>\ m^{-1.5}\times \left(\frac{v_{\rm i}}{10^4\ \mathrm{km\ s^{-1}}}\right)^{1.5}\left(\frac{t_{\rm i}}{45\ \mathrm{days}}\right)^{1.5}\left(\frac{t}{t_{\rm i}}\right)^{1.5m}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{0.68} \quad (4)$$

where, since the appearance of optical lines for measuring SN ejecta velocities is often delayed a bit relative to the time of the explosion, they arbitrarily take $t_{\rm i} =$ 45 days. Because observations have shown that, generally, $0.8 \leq m \leq 1.0$ and from equation 4 $\dot{M} \propto t_{\rm i}^{1.5(1-m)}$, the dependence of the calculated mass-loss rate on the date $t_{\rm i}$ of the initial ejecta velocity measurement is weak ($\dot{M} \propto t_{\rm i}^{<0.3}$), so that the best optical or VLBI velocity measurements available can be used without worrying about the deviation of the exact measurement epoch from the assumed 45 days after explosion. For convenience, and because many SN measurements indicate velocities of $\sim 10,000$ km s^{-1}, one usually assumes $v_{\rm i} = v_{\rm blastwave} = 10,000$ km s^{-1}, CSM temperature $T = 2\times10^4$ K, appropriate for a RSG wind), time $t = (t_{6\ \rm cm\ peak} - t_0)$ days from best fits to the radio data for each RSN, and m from Equation 3.

The assumed pre-SN wind velocity, $w_{\rm wind} = 10$ km s^{-1}, appropriate for a red supergiant (RSG) wind can also be generally applied to red giant companions in symbiotic systems and to recurrent novae (e.g., the CSM from the red giant wind in RS Oph is $\lesssim 20$ km s^{-1}; Hachisu Kato 2001). However, one should note that Shore et al. (1996) assume for RS Oph a red giant terminal velocity of $50-$ -100 km s^{-1}, and Solf, Böhm & Raga (1986) find bipolar winds in symbiotic systems with speeds in excess of 100 km s^{-1}. For the case of possible dwarf and subdwarf winds, one would expect velocities of the order of their escape velocities, i.e. few hundred km s^{-1}, but also much lower mass loss rates. Therefore, in these cases any mass transfer induced by stellar winds would have no effect on building up a dense CSM environment, and can safely be neglected in our discussion.

4. APPLICATION TO TYPE IA SUPERNOVAE

Since the overall shape of the optical light curves of SNe Ia are rather similar to those of SNe Ib/c (although SNe Ib/c are generally ∼1–1.5 mag fainter than SNe Ia; see e.g., Leibundgut et al. 1991), suggesting comparable envelope masses and structures, we will adopt for our analysis average parameters measured for SNe Ib/c (see Weiler et al. 2002), namely $\alpha = -1.1$, $\beta = -1.5$, and $\delta = -2.6$. This is very similar to the approach taken by Boffi et al. (1995), where they argued that, in particular for a symbiotic stellar system progenitor scenario, many of the parameters expected for SNe Ia (specifically, SN 1986G in their case) may be analogous to those for SNe Ib/c.

As discussed earlier, the SN radio emission is a function of the CSM density and, hence, is proportional to the ratio of the mass-loss rate to the wind velocity, $\dot{M}/w$. The theory developed by Chevalier (1982a,b) provides a functional dependence between the intrinsic (*i.e.,* before external f-f absorption by an ionized CSM) radio luminosity and the density of the CSM, of the form (Weiler et al. 1989, 2002)

$$L_{\rm intrinsic}(\nu) \propto (\dot{M}/w)^{(\gamma-7+12m)/4} m^{(5+\gamma)/2}\times t^{-(\gamma+5-6m)/2}\nu^{-(\gamma-1)/2}, \quad (5)$$

where

$$\gamma = 1 - 2\alpha. \quad (6)$$

For the assumed $\alpha = -1.1$ ($\gamma = 3.2$), $\delta = -2.6$ ($m = -\delta/3 = 0.87$), and at $\nu = 5$ GHz, this becomes

$$L_{\rm intrinsic}(\nu) \propto (\dot{M}/w)^{1.65} t^{-1.5}\nu^{-1.1}. \quad (7)$$

Multiplying by the attenuation produced by external (f-f) absorption, it becomes analogous to Equation (1), but when expressed in absolute units is

$$\frac{L}{10^{26}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}} = \Lambda\left(\frac{\dot{M}(\mathrm{M_\odot\ yr^{-1}})}{w_{\rm wind}/10\ \mathrm{km\ s^{-1}}}\right)^{1.65}\times \left(\frac{\nu}{5\mathrm{GHz}}\right)^{-1.1}\left(\frac{t-t_0}{\mathrm{days}}\right)^{-1.5} e^{-\tau_{\rm CSM_{external}}} \quad (8)$$

The parameter Λ is a proportionality constant which is not provided by theory and must be calibrated empirically from radio observations of SNe Ib/c. Since we are dealing with sources that are intrinsically faint, we calibrate Λ using the best measured faint SN Ib/c, namely SN 1983N (Sramek et al. 1984, Weiler et al. 1989, 2002), obtaining

$$\Lambda = 1285 \pm 245. \quad (9)$$

The quoted error corresponds to the combination in quadrature of the uncertainty of the light curve fit (∼ 14%) as given by Weiler et al. (1986) and an estimated uncertainty in the distance to M83 of ∼ 7% (Thim et al. 2003). Also, one should be aware that appreciably different values of Λ would be obtained from using different SNe Ib/c listed in table 3 of Weiler et al. (2002) for its estimation, with the bright SNe providing systematically lower values than the fainter ones, with a range of a factor of 10 between the extremes. However, because of the functional dependence of L on $\dot{M}/w_{\rm wind}$, such a spread would result in an overall uncertainty in $\dot{M}$ of at most a factor of two.

For each SN the upper limit to the mass-loss rates were estimated by direct comparisons of the radio luminosity upper limits with a set of theoretical light curves calculated for all relevant epochs and for values of the parameter $\dot{M}/w_{\rm wind}$ between 10^{-9} and 10^{-6} $\mathrm{M_\odot\ yr^{-1}\ km^{-1}}$ s at logarithmic steps of 0.05. In the case of SNe with observations at different frequencies, the overall upper limit to $\dot{M}/w_{\rm wind}$ was taken as the minimum value among those determined for each frequency. Finally, the mass-loss rates were calculated assuming the wind velocity to be

$w = 10$ km s^{-1}, as appropriate for winds from red giants and RSGs, as well as from binary systems with total mass of a few solar masses and separations of a few AU.

Table 1 lists upper limits to the mass-loss rates from the SN Ia progenitor systems. Column 1 lists the SN name, and column 2 its distance taken from direct Cepheid determinations, whenever possible, or from the Revised Shapley-Ames Catalog of Bright Galaxies (Sandage & Tammann 1987) rescaled to a value of the Hubble constant $H_0 = 63$ km s^{-1} Mpc^{-1} (Panagia 2003). Columns 3, 4, and 5 list the epoch, the wavelength, and the 2σ limit to the spectral luminosity that yielded the lowest mass-loss rate limit, and the last column (6) lists the 2σ limit to the mass-loss rate, $\dot{M}$.

5. DISCUSSION

Examination of Table 1 shows that our upper limits are generally consistent with pre-SN mass-loss rates lower than 10^{-6} M$_\odot$ yr^{-1} associated with the progenitor system, with almost half (actually 12 out of 27) of the 2σ limits falling below $\sim 4 \times 10^{-7}$ M$_\odot$ yr^{-1}. In particular, the most stringent upper limits are provided by the observations of SNe 1989B and 1998bu, as shown in Figure 2. Not surprisingly, it also appears that most of the lowest upper limits are found for relatively nearby SNe Ia observed at early epochs, *e.g.,* $\sim$ 10–50 days after explosion or about -10 to $+30$ days relative to the optical maximum, and at frequencies 5–8.3 GHz ($\lambda = 3.6$–6 cm). This is because the VLA sensitivity is highest in the 5 and 8.3 GHz bands and the expected radio light curves at these frequencies peak around epochs of 10 days for mass-loss rates of $\sim 10^{-7}$ M$_\odot$ yr^{-1}. On this basis, we argue that future searches should focus their efforts in the 5 and 8.3 GHz bands, making prompt observations of SNe Ia soon after they are discovered, and repeating the observations about every ten days until one or two months past the optical maximum. Additional observations at later times and at longer wavelengths would also be useful to check on the possibility that a non-detection may be due to strong (f-f) absorption (*i.e.,* indicating a *high* mass-loss rate), rather than merely to intrinsically faint emission.

We can derive a more stringent limit if we assume that *all* SNe Ia have the same type of progenitors and that they reach the explosion along identical evolutionary paths. In this case, we can combine the upper limits derived for individual objects, because they could be considered as the "errors" in a series of independent measurements, *i.e.,* $\sigma^2_{\rm combined} = 1/\Sigma_i(1/\sigma_i^2)$. In this way, we obtain a combined 2σ upper limit of $\lesssim 2.6 \times 10^{-8}$ M$_\odot$ yr^{-1}.

Such low mass-loss rates as we have estimated generally rule out any red giant or red supergiant SN progenitors (consistent with current theories), and also exclude any SN Ia progenitor models that invoke a stellar wind from a (massive) companion to provide the required accretion rate onto a WD. Nomoto et al. (1984) calculated that only accretion rates appreciably greater than $\sim 4 \times 10^{-8}$ M$_\odot$ yr^{-1} can lead to a mass increase of the accreting WD resulting in a SN Ia explosion. More recently, Prialnik & Kovetz (1995) estimate that accretion rates $\gtrsim 10^{-7}$ M$_\odot$ yr^{-1} are needed for a WD to increase its mass so as to exceed the Chandrasekhar mass.

Since accretion from a companion star's wind is a rather inefficient process, with $\sim$10% of the wind material being accreted onto a WD Yungelson et al. (1995), only stellar companions with mass-loss rates $\gtrsim 4 - 10 \times 10^{-7}$ M$_\odot$ yr^{-1} would be able to satisfy the requirement. These $\dot{M}$ values are much greater ($\sim$10–25 times) than the best individual, and particularly the aggregate, upper limits derived from our SN Ia radio observations. Thus, we support the conclusion reached by Boffi et al. (1995) and Eck et al. (1995) that symbiotic systems are unlikely to be SN progenitors.

An alternative to wind accretion onto the WD is Roche lobe overflow from a giant, subgiant, or main sequence companion (see Branch et al. 1995, Livio 2001), so that the process is more gradual and efficient. In this case our best combined upper limit, *i.e.,* 2.6×10^{-8} M$_\odot$ yr^{-1}, implies that such a mass transfer must have an efficiency of $\gtrsim$ 60–80 % (depending on the adopted limiting accretion rate for WDs to become SNe Ia) to avoid leaving a residual CSM from which synchrotron emission would be detectable at current radio limits.

Double degenerate models for SN Ia events, in which the explosion is triggered by the merger of two WDs in a binary system are, of course, still consistent with our observations.

One should keep in mind that our mass-loss rate estimates are dependent on the assumptions that SNe Ia radio light curves will be very similar to those of SNe Ib/c and that $w_{\rm wind} = 10$ km s^{-1}, $v_{\rm i} = 10^4$ km s^{-1}, and $T = 2 \times 10^4$ K, with dependences shown in Equations 4 and 8. Even if higher values for any of these quantities are more appropriate or realistic, and will therefore yield higher mass-loss limits and correspondingly less stringent limits on the properties of the progenitor systems, we can definitely rule out the symbiotic system scenario based on our complete dataset.

6. CONCLUSIONS

No radio emission has been found from 27 SNe Ia observed over two decades with the VLA. It is clear that the CSM environment is far more tenuous than that of SNe II, or even SNe Ib/c. Using model predictions of radio emission from SNe and assuming that the radio properties of SNe Ia would be relatively similar to those of SNe Ib/c (at least for some progenitor system models), but with a wind-established CSM from a less massive pre-SN system, we can place constraints on the mass-loss rate from such systems. If SNe Ia originate from mass accretion from a massive companion's wind onto a WD, we can establish a stringent limit of $\dot{M} \lesssim 3 \times 10^{-8}$ M$_\odot$ yr^{-1} in the best cases. This severely limits the possibility that the progenitors are symbiotic systems, where the companion is a red giant or supergiant star. However, high-efficiency mass transfer through Roche lobe overflow from a lower mass companion or the double degenerate scenario, involving the merger of a two WDs or a WD and a neutron star, cannot be ruled out.

We note that even in the most unusual case so far, of the recent SN Ia 2002ic, which exhibited optical evidence for a substantial CSM (Hamuy et al. 2003), it was concluded that the double degenerate scenario was the most consistent model for the progenitor of that event (Hamuy et al. 2003, Livio & Riess 2003). Attempts to detect radio emission from SN 2002ic with the VLA were unsuccessful, likely due to the SN's large distance (Stockdale

et al. 2003, Berger et al. 2003). Another recent example appears to be SN 2005gj (Prieto et al. 2005), which has also not been detected using the VLA (Soderberg & Frail 2005). We further note, of course, that such events are likely intrinsically quite rare in general.

Clearly, additional observations of new SNe Ia should be made with the VLA as early and as deeply after discovery as possible, to help further constrain the nature of SN Ia progenitors. We continue to attempt observations such as these. However, with the current VLA, based on the results presented in this paper, realistically only the next Local Group SN Ia, or possibly a SN in a nearby galaxy group, will provide greatly improved upper limits. The plans for the Expanded VLA[9], and the far greater sensitivity that the upgrade will produce, will likely soon afford us with an unprecedented opportunity to detect radio emission from SN Ia and help define their progenitor systems. Considering the cosmological implications, such future observations are essential.

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[9] http://www.nrao.edu/evla/.

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TABLE 1
OBSERVED SNE

SN Name	Date of Optical Maximum[a]	Magnitude At Maximum[a]	SN Position (J2000.0) R. A.	SN Position (J2000.0) Decl.	Parent Galaxy Name	Parent Galaxy Type
1980N	1980 Dec 11	12.5B	$03^h22^m59\overset{s}{.}8$ $\pm1\overset{s}{.}3$	$-37°12'48''$ $\pm15\overset{''}{.}0$	NGC 1316	S0
1981B	1981 Mar 12	12.0B	12 34 29.57 ±0.07	+02 11 59.3 ±1.0	NGC 4536	Sbc
1982E	≤1982 Mar	≤14pg	03 26 40.41 ±0.54	−21 17 13.8 ±8.0	NGC 1332	S0
1983G	1983 Apr 09	12.9B	12 52 21.0 ±1.0	−01 12 12 ±15.0	NGC 4753	S0 pec
1984A	1984 Jan 16	12.4B	12 26 55.73 ±0.06	+15 03 17.1 ±1.0	NGC 4419	SBab
1985A	≤1985 Jan	≤14.5pg	09 13 42.43 ±0.30	+76 28 23.8 ±1.0	NGC 2748	Sc
1985B	≤1985 Jan	≤13.0V	12 02 43.94 ±0.07	+01 58 45.3 ±1.0	NGC 4045	Sbc
1986A	1986 Feb 07	14.4B	10 46 36.59 ± 0.07	+13 45 00.7 ± 1.0	NGC 3367	SBc
1986G	1986 May 11	12.5B	13 25 36.51 ± 0.07	−43 01 54.3 ± 1.0	NGC 5128	S0+Spec
1986O	∼1986 Dec 20	∼14.0V	06 25 58.0 ± 0.58	−22 00 42 ± 8.0	NGC 2227	SBcd
1987D	1987 Apr 17	13.7B	12 19 41.10 ± 0.07	+02 04 26.6 ± 1.0	M+00−32−01	Sbc
1987N	≤1987 Dec	≤13.4V	23 19 03.42 ± 0.07	−08 28 37.5 ± 1.0	NGC 7606	Sb
1989B	1989 Feb 06	12.5B	11 20 13.93 ± 0.07	+13 00 19.3 ± 1.0	NGC 3627	Sb
1989M	∼1989 Jun	≤12.1B	12 37 40.75 ± 0.07	+11 49 26.1 ± 1.0	NGC 4579	Sab
1990M	∼1990 Jun	≤13.4V	14 08 29.3 ± 0.1	−05 02 36 ± 1.0	NGC 5493	S0
1991T	1991 Apr 28.5	11.64B	12 34 10.20 ± 0.07	+02 39 56.4 ± 1.0	NGC 4527	Sb
1991bg	1991 Dec 14.7	13.95V	12 25 03.70 ± 0.07	+12 52 15.6 ± 1.0	NGC 4374	E1
1992A	1992 Jan 16	12.78V	03 36 27.41 ± 0.07	−34 57 31.4 ± 1.0	NGC 1380	S0/Sa
1994D	1994 Mar 22	11.85V	12 34 02.40 ± 0.007	+07 42 05.7 ± 0.1	NGC 4526	SAB(s)
1995al	1995 Nov 09	13.25V	09 50 55.97 ± 0.06	+33 33 09.4 ± 1.0	NGC 3021	SAbc:
1996X	1996 Apr 18	13.24B	13 18 01.13 ± 0.06	−26 50 45.3 ± 1.0	NGC 5061	E0
1998bu	1998 May 21	11.93V	10 46 46.03 ± 0.03	+11 50 07.1 ± 0.5	NGC 3368	SABab
1999by	1999 May 10	13.8B	09 21 52.07 ± 0.04	+51 00 06.6 ± 1.0	NGC 2841	SA(r)b
2002bo	2002 Mar 23	14.04B	10 18 06.51 ± 0.03	+21 49 41.7 ± 0.5	NGC 3190	SA(s)a
2002cv	2002 May 20	14.8J	10 18 03.68 ± 0.03	+21 50 06.0 ± 0.5	⋯	⋯
2003hv	2003 Sep 08	<12.5R	03 04 09.32 ± 0.03	−26 05 07.5 ± 0.5	NGC 1201	SA(r)0
2003if	2003 Sep 01	<17.6R	03 19 52.61 ± 0.03	−26 03 50.5 ± 0.5	NGC 1302	SAB(r)a

[a]Date and magnitude at discovery if the information is not available for the SN maximum.

TABLE 2
Observations

SN Name	Observation Date	Age[a] (days)	VLA Config.	Map rms (1σ)					
				σ_{20} (mJy)	σ_{6} (mJy)	$\sigma_{3.6}$ (mJy)	σ_{2} (mJy)	$\sigma_{1.3}$ (mJy)	$\sigma_{0.7}$ (mJy)
1980N	1981 Feb 03	72	A	···	0.20	···	···	···	···
1981B	1981 Mar 11	18	A	···	0.10	···	···	···	···
	1981 Apr 09	46	A	···	0.13	···	···	···	···
	1981 May 14	82	B	···	0.17	···	···	···	···
	1981 Jun 19	117	B	···	0.20	···	···	···	···
	1981 Aug 13	172	B	···	0.30	···	···	···	···
	1981 Nov 11	261	C	···	0.07	···	···	···	···
	1982 Feb 27	369	A	···	0.03	···	···	···	···
	1982 Jun 25	489	A	···	0.07	···	···	···	···
	1982 Oct 02	587	A	···	0.07	···	···	···	···
	1983 Feb 16	723	C	···	0.20	···	···	···	···
1982E	1985 Dec 29	1417	D	0.18	0.07	···	···	···	···
1983G	1983 May 27	72	C	···	0.07	···	···	···	···
1984A	1984 Mar 05	430	BnC	···	0.10	···	···	···	···
1985A	1985 Feb 01	49	A	···	0.07	···	···	···	···
	1985 Feb 08	56	A	0.07	···	···	···	···	···
	1985 Feb 17	65	A	0.09	0.07	···	···	···	···
	1985 Mar 02	81	A	0.07	···	···	···	···	···
	1985 Apr 05	114	A/B	0.08	···	···	···	···	···
	1985 Oct 28	320	C/D	0.10	···	···	···	···	···
	1986 Jun 15	550	A/B	0.24	0.14	···	···	···	···
	1987 Oct 23	1045	A/B	0.26	0.09	···	···	···	···
1985B	1985 Feb 22	70	A	0.17	0.19	···	···	···	···
	1985 Mar 18	94	A/B	0.40	0.06	···	···	···	···
	1985 Sep 15	275	C	0.08	0.05	···	···	···	···
	1986 Apr 30	502	A	···	0.16	···	···	···	···
	1987 Sep 18	1008	A	···	0.07	···	···	···	···
1986A	1986 Feb 07	18	D	···	0.22	···	···	···	···
	1986 Feb 25	36	A	0.36	0.12	···	···	···	···
	1986 Mar 16	55	A	···	0.05	···	···	···	···
	1986 Apr 03	73	A	···	0.09	···	···	···	···
	1986 Jun 15	146	A/B	0.15	0.09	···	···	···	···
	1986 Oct 16	269	B/C	0.25	0.08	···	···	···	···
	1987 Apr 01	436	D	···	0.08	···	0.15	···	···
1986G	1986 May 14	21	A	···	1.06	···	···	···	···
	1986 May 21	28	A	···	0.70	···	3.21	···	···
	1986 Jun 08	46	A	7.48	1.02	···	···	···	···
	1986 Jul 06	74	A/B	···	1.52	···	1.32	···	···
	1986 Sep 20	150	C	···	2.49	···	1.27	···	···
	1987 Jan 04	256	C	···	2.71	···	1.38	···	···
	1987 Oct 23	548	A/B	5.06	1.31	···	4.47	···	···
	1989 Apr 06	1079	B	···	4.08	···	···	···	···
1986O	1987 Feb 12	72	C/D	0.80	0.07	···	0.18	···	···
	1987 Apr 11	130	D	···	0.08	···	0.16	···	···
	1987 May 24	173	D	···	0.08	···	0.15	···	···
	1987 Aug 28	269	A	···	0.07	···	···	···	···
	1988 Apr 03	488	C	0.49	0.06	···	···	···	···
	1989 Jul 17	958	C	···	0.08	···	···	···	···
1987D	1987 May 15	46	D	···	0.20	···	···	···	···
	1987 Jun 04	66	D	···	0.26	···	···	···	···
	1987 Jun 21	83	A	···	0.06	···	···	···	···
	1987 Sep 18	172	A	···	0.07	···	···	···	···
	1988 May 29	426	C/D	···	0.26	···	···	···	···
1987N	1987 Dec 20	37	B	0.13	0.10	···	···	···	···
	1988 Jan 12	60	B	0.10	0.08	···	···	···	···
	1988 Feb 01	76	B	0.11	0.09	···	···	···	···
	1988 Mar 31	135	C	0.23	0.07	···	···	···	···
	1988 Apr 11	146	C	0.22	0.40	···	···	···	···
	1988 Aug 22	279	D	···	0.08	···	···	···	···
	1989 Apr 24	524	B	···	0.06	···	···	···	···
1989B	1989 Feb 02[b]	10	A	···	0.08	0.06	···	···	···
	1989 Feb 03	11	A	···	0.03	0.03	···	···	···
	1989 Mar 06	42	A/B	···	0.06	···	···	···	···
	1989 Mar 27	63	B	···	0.06	···	···	···	···
	1989 Apr 06	73	B	···	0.07	···	···	···	···
	1989 May 15	112	B/C	···	0.06	···	···	···	···
	1990 Jul 22	545	B	···	···	0.04	···	···	···
	1993 Oct 25	1736	C/D	···	···	0.04	···	···	···
	2003 May 26	5236	A	···	···	···	···	···	···
1989M	1989 Jul 17	60	C	···	0.13	···	···	···	···
	1989 Sep 04	109	C	···	0.10	···	···	···	···
	1989 Oct 24	159	C/D	···	0.07	···	···	···	···
	1989 Dec 21	217	D	···	0.05	···	···	···	···
	1990 Feb 13	271	D/A	···	0.08	···	···	···	···
	1990 May 29	376	A	···	0.15	···	···	···	···

TABLE 2
OBSERVATIONS (CONT.)

SN Name	Observation Date	Age[a] (days)	VLA Config.	Map rms (1σ) σ_{20} (mJy)	σ_{6} (mJy)	$\sigma_{3.6}$ (mJy)	σ_{2} (mJy)	$\sigma_{1.3}$ (mJy)	$\sigma_{0.7}$ (mJy)
1990M	1990 Jun 29	42	A/B	...	...	0.04	...	...	...
	1990 Dec 14	210	C	...	...	0.04	...	...	...
1991T	1991 May 08	24	D	...	...	0.05	0.06	...	...
	1991 Jul 09	86	A	...	...	0.06	0.20	...	...
	1993 Feb 02	660	A/B	0.05	...	0.05	...	...	...
1991bg	1991 Dec 26	26	B	0.26	...	0.16	...	...	...
	1993 Feb 02	430	A/B	0.14[c]	...	0.08	...	...	...
	1993 Oct 25	695	C/D	...	...	0.20[b]	...	...	...
1992A	1992 Jan 27	25	B/C	...	0.03	...	...	...	...
	1992 Oct 09	281	A	...	0.15	...	...	...	...
	1993 Feb 05	400	A/B	...	0.08	...	...	...	...
1994D	1994 May 04	57	A	...	0.06	...	...	...	...
1995al	1995 Nov 08	13	B	0.08	...	...	...	...	...
1996X	1996 May 29	55	DnC	...	...	0.09	...	...	...
1998bu	1998 May 13	6	A	...	...	0.07	...	...	...
	1998 May 31	24	A	...	...	0.04	0.18	...	...
	1998 Jun 09	33	AnB	...	...	0.05	0.23	...	...
	1999 Jan 07	245	C	...	0.07	0.06	...	...	...
1999by	1999 May 07	11	D	...	...	0.07	...	...	...
	1999 May 24	28	D	...	...	0.08	...	...	...
2002bo	2002 May 21	73	AnB	...	...	0.06	0.28	0.36	0.62
	2002 Jun 12	95	B	0.06	0.08	0.07	...	...	...
2002cv	2002 May 21	19	AnB	...	...	0.06	0.28	0.36	0.62
	2002 Jun 12	41	B	0.06	0.08	0.07	...	...	...
2003hv	2003 Oct 21	57	B	...	...	0.05	...	...	...
2003if	2003 Oct 21	64	B	...	...	0.05	...	...	...

[a]The explosion date is taken to be 18 days before the date of the optical maximum (Goldhaber et al. 2001).
[b]Observations were graciously contributed by R. Brown.
[c]Severely confused by the southern radio lobe from the host galaxy, NGC 4374.

TABLE 3
LOWEST UPPER LIMITS TO SN IA PROGENITOR MASS-LOSS RATES

SN	Distance (Mpc)	Epoch (days)	Wavelength (cm)	Radio Luminosity[a] (erg s^{-1} Hz^{-1})	$\dot{M}$ [b] ($M_\odot$ yr^{-1})
1980N	23.3	71	6	2.5×10^{26}	1.1×10^{-6}
1981B	16.6	17	6	6.5×10^{25}	1.3×10^{-7}
1982E	23.1	1416	20	2.3×10^{26}	7.3×10^{-6}
1983G	17.8	71	6	5.0×10^{25}	4.1×10^{-7}
1984A	17.4	74	6	7.1×10^{25}	5.3×10^{-7}
1985A	26.8	55	20	1.2×10^{26}	2.5×10^{-7}
1985B	28.0	69	20	3.1×10^{26}	6.1×10^{-7}
1986A	46.1	57	6	2.6×10^{26}	9.2×10^{-7}
1986G	5.5	28	6	5.0×10^{25}	1.7×10^{-7}
1986O	28	71	6	1.3×10^{26}	7.4×10^{-7}
1987D	30	83	6	1.3×10^{26}	8.4×10^{-7}
1987N	37.0	67	20	4.2×10^{26}	7.4×10^{-7}
1989B	11.1	15	3.6	8.1×10^{24}	3.3×10^{-8}
1989M	17.4	50	6	9.2×10^{25}	4.4×10^{-7}
1990M	39.4	32	3.6	1.5×10^{26}	5.4×10^{-7}
1991T	14.1	28	3.6	2.3×10^{25}	1.5×10^{-7}
1991bg	17.4	29	3.6	1.1×10^{26}	2.0×10^{-7}
1992A	24.0	29	6	4.1×10^{25}	1.6×10^{-7}
1994D	14	61	6	2.8×10^{25}	2.5×10^{-7}
1995al	30	17	20	1.7×10^{26}	1.2×10^{-7}
1996X	30	66	3.6	1.9×10^{26}	1.2×10^{-6}
1998bu	11.8	28	3.6	1.3×10^{25}	1.1×10^{-7}
1999by	11.3	15	3.6	2.1×10^{25}	8.0×10^{-8}
2002bo	22	95	20	6.8×10^{25}	3.0×10^{-7}
2002cv	22	41	20	6.8×10^{25}	3.0×10^{-7}
2003hv	23	61	3.6	6.2×10^{25}	5.8×10^{-7}
2003if	26.4	68	3.6	8.1×10^{25}	7.6×10^{-7}

[a]The spectral luminosity upper limit (2σ), as estimated at the wavelength given in column (4), which, when combined with the age of the SN at the time of observation, yielded the lowest mass-loss rate limit.

[b]The upper limit (2σ) to the mass-loss rate, $\dot{M}$, is calculated from the spectral luminosity lowest upper limit given in column (5), as measured at the wavelength given in column (4) at an epoch after explosion given in column (3). The mass-loss limits are calculated with the assumption that the SN Ia progenitor systems can be modeled by the known properties of SNe Ib/c progenitor systems, and that the pre-SN wind velocity establishing the CSM is $w_{\rm wind} = 10$ km s^{-1}.

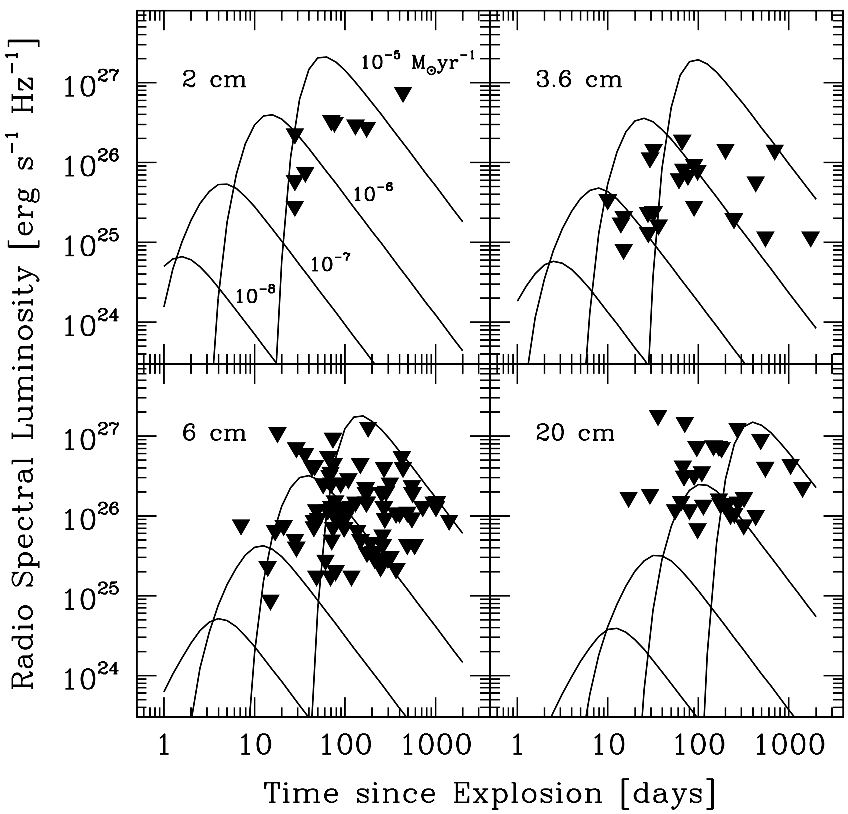

FIG. 1.— The upper limits (2σ) for all observed SNe Ia at 2, 3.6, 6, and 20 cm wavelength. Shown as examples are model radio light curves appropriate for SNe Ib/c (see text), assuming mass-loss rates associated with the progenitor systems of 10^{-8}, 10^{-7}, 10^{-6}, and 10^{-5} $M_\odot$ yr^{-1} in a stellar wind with speed of $w_{\rm wind} = 10$ km s^{-1}.

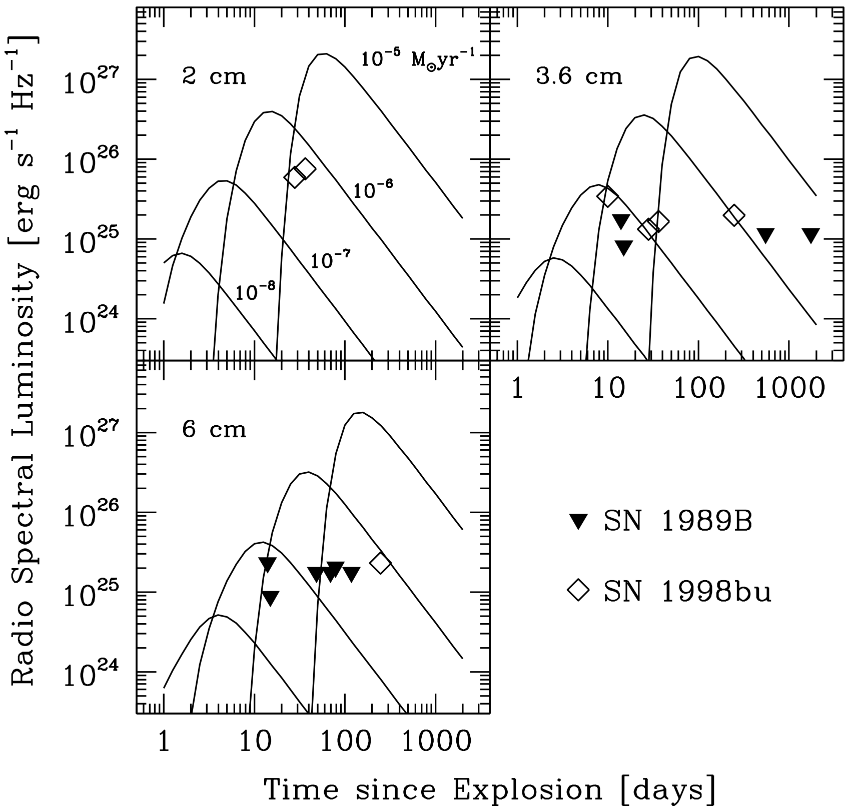

FIG. 2.— The upper limits (2σ) for SN 1989B at 2, 3.6, and 6 cm wavelength (*filled triangles*) and SN 1998bu at 3.6 and 6 cm wavelength (*open diamonds*), compared with model radio light curves appropriate for SNe Ib/c (see text), assuming mass-loss rates associated with the progenitor systems of 10^{-8}, 10^{-7}, 10^{-6}, and 10^{-5} $M_{\odot}$ yr^{-1} in a stellar wind with speed $w_{\rm wind} = 10$ km s^{-1}.